United States Patent [19]
Seidel

[11] 3,818,642
[45] June 25, 1974

[54] GRINDING MACHINE

[75] Inventor: William B. Seidel, Birmingham, Mich.

[73] Assignee: The Babcock & Wilcox Company, New York, N.Y.

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[21] Appl. No.: 294,616

[52] U.S. Cl. 51/165.8, 51/165.87
[51] Int. Cl. B24b 49/16
[58] Field of Search .... 51/165 R, 165.8, 165.81, 51/165.87

[56] References Cited

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Primary Examiner—Harold D. Whitehead
Attorney, Agent, or Firm—Barns, Kisselle, Raisch & Choate

[57] ABSTRACT

A grinding machine wherein the griding wheel is moved relative to the workpiece by a screw rotated by an electric motor that produces a torque that is proportional to the current applied thereto. The movement of the grinding wheel is controlled in an improved constant force mode or an improved constant rate mode or in an improved combination of both modes.

71 Claims, 13 Drawing Figures

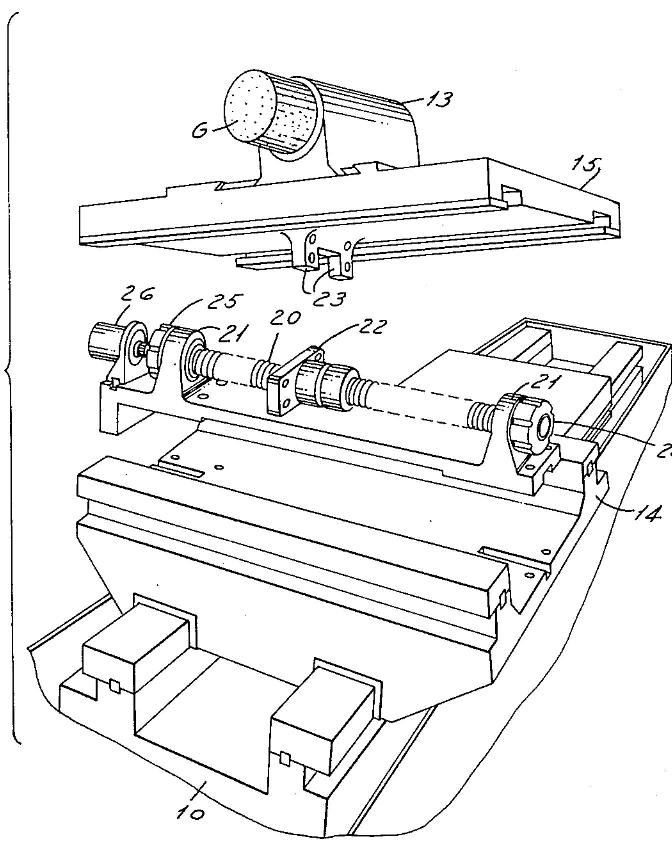


FIG. 1

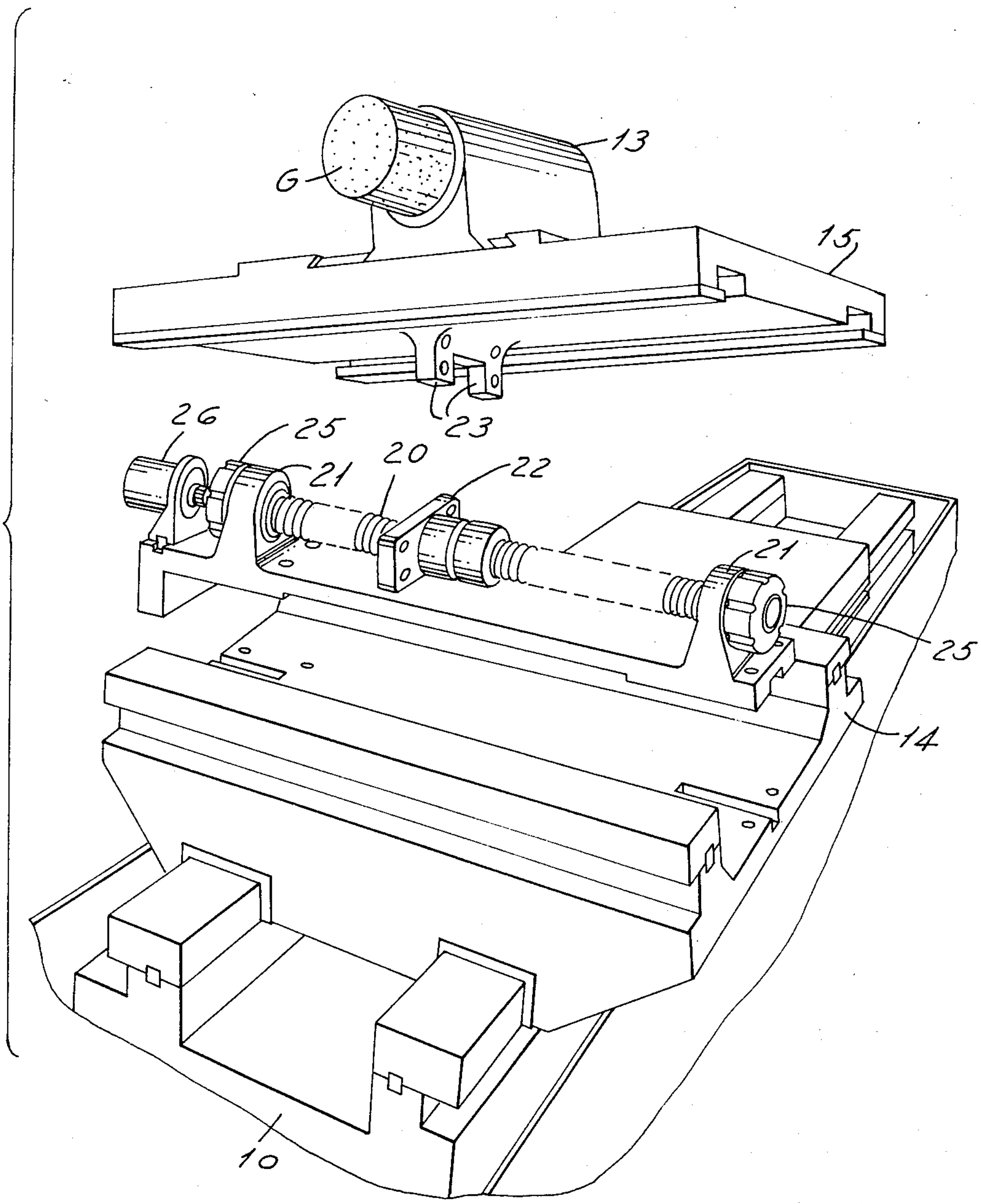


FIG. 3

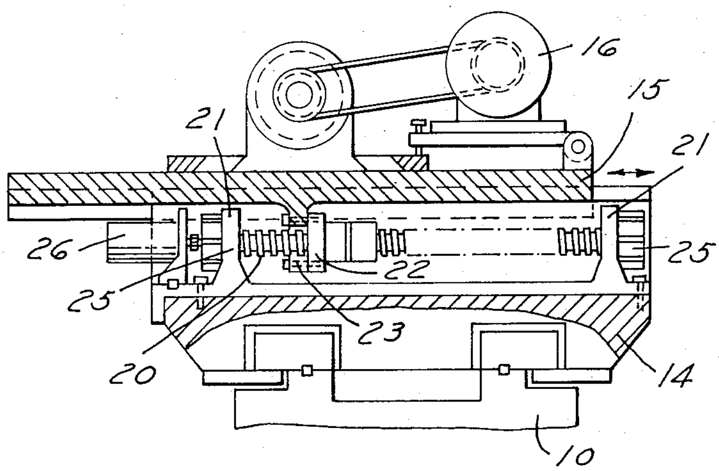


FIG. 2

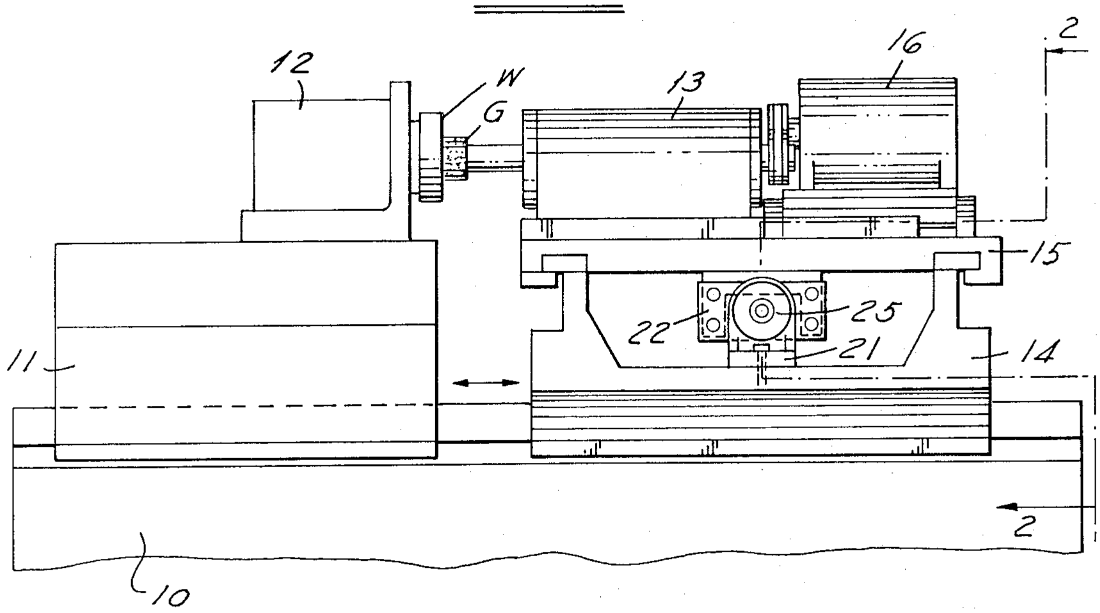


FIG. 5

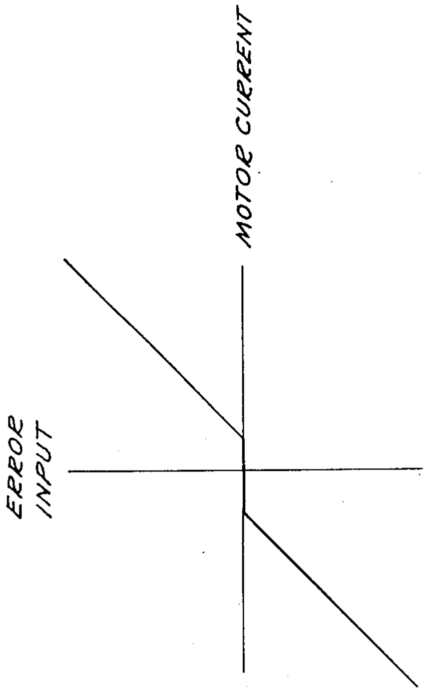


FIG. 4

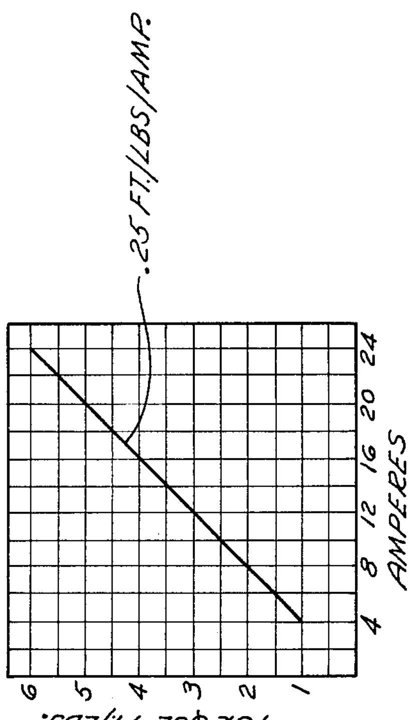


FIG. 6

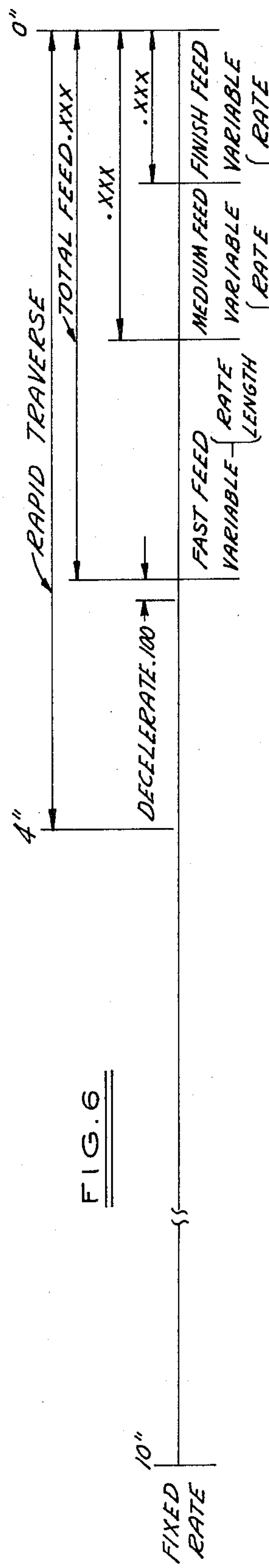


FIG. 7

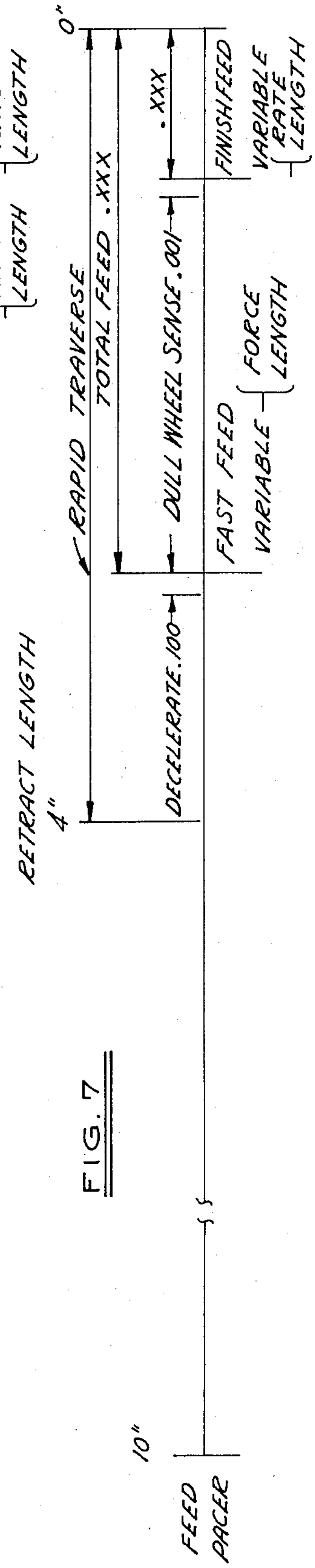
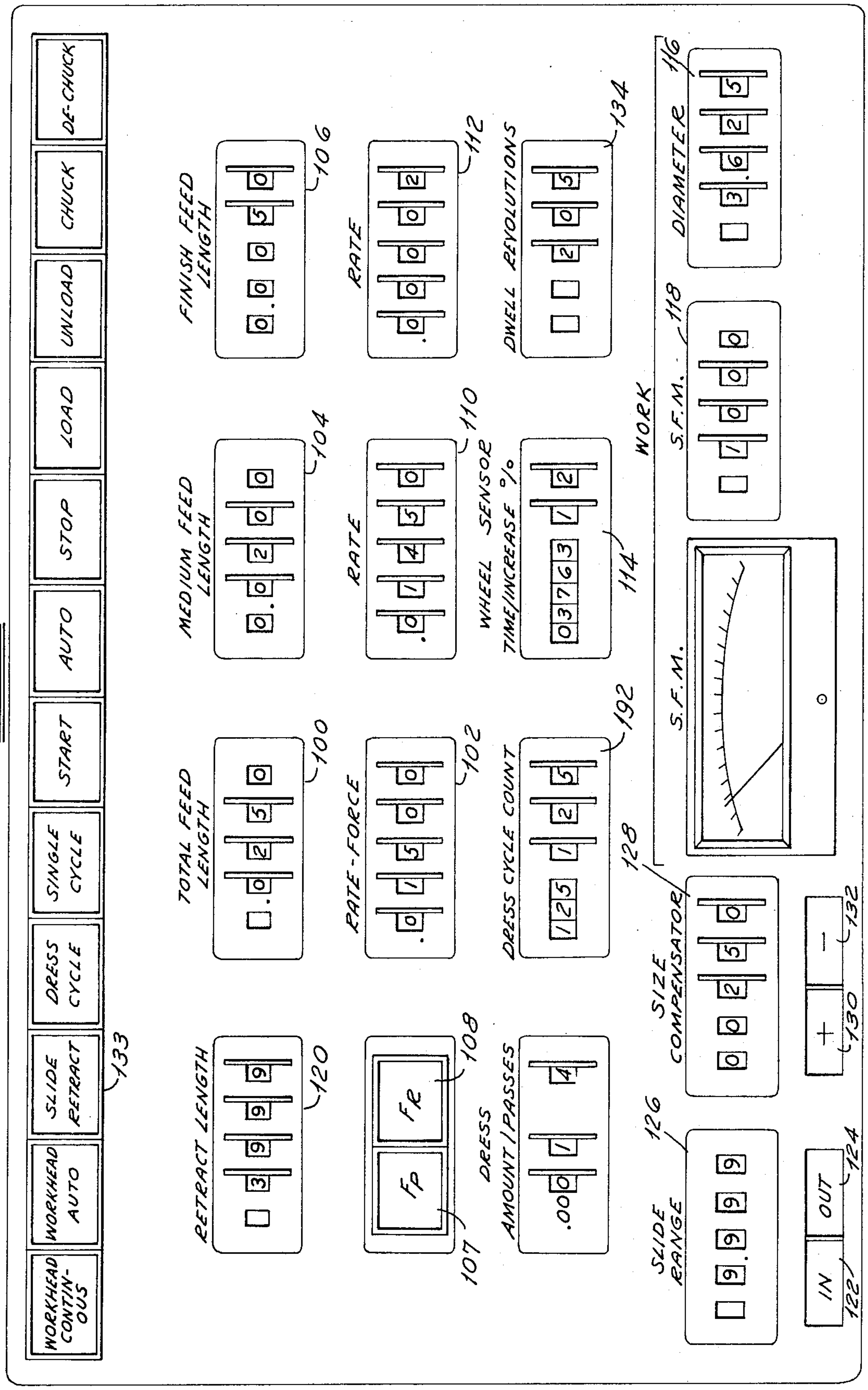


FIG. 8


WORKHEAD CONTIN-OUS
WORKHEAD AUTO
SLIDE RETRACT
DRESS CYCLE
SINGLE CYCLE
START
AUTO
STOP
LOAD
UNLOAD
CHUCK
DE-CHUCK
133
RETRACT LENGTH
120
TOTAL FEED LENGTH
100
MEDIUM FEED LENGTH
104
FINISH FEED LENGTH
106
F_P
F_R
107
108
RATE-FORCE
102
RATE
110
RATE
112
DRESS AMOUNT/PASSES
DRESS CYCLE COUNT
192
WHEEL SENSOR TIME/INCREASE %
114
DWELL REVOLUTIONS
134
SLIDE RANGE
126
SIZE COMPENSATOR
128
S.F.M.
WORK S.F.M.
118
DIAMETER
116
IN
122
OUT
124
+
130
−
132

PATENTED JUN 25 1974

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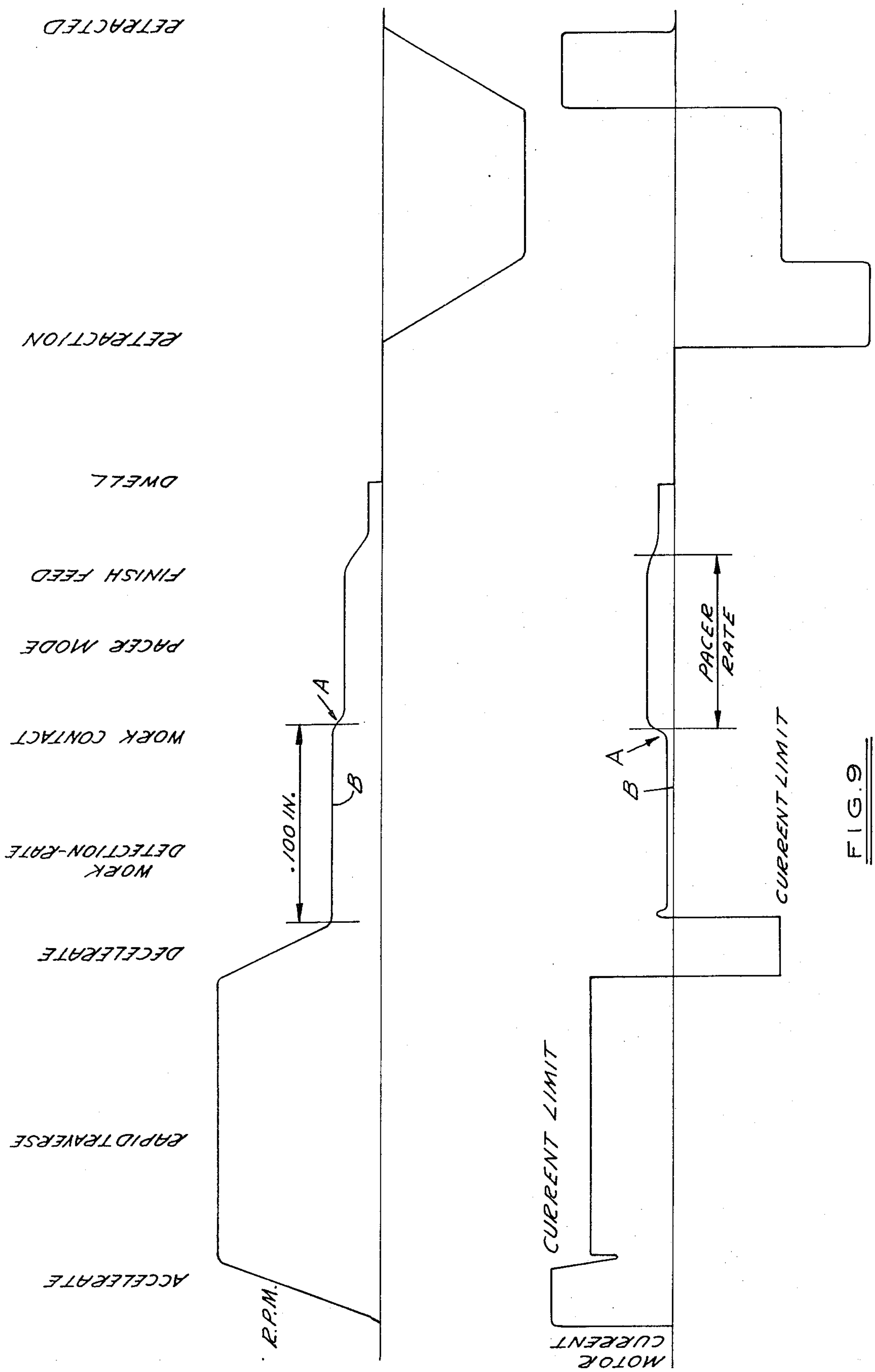

FIG. 9

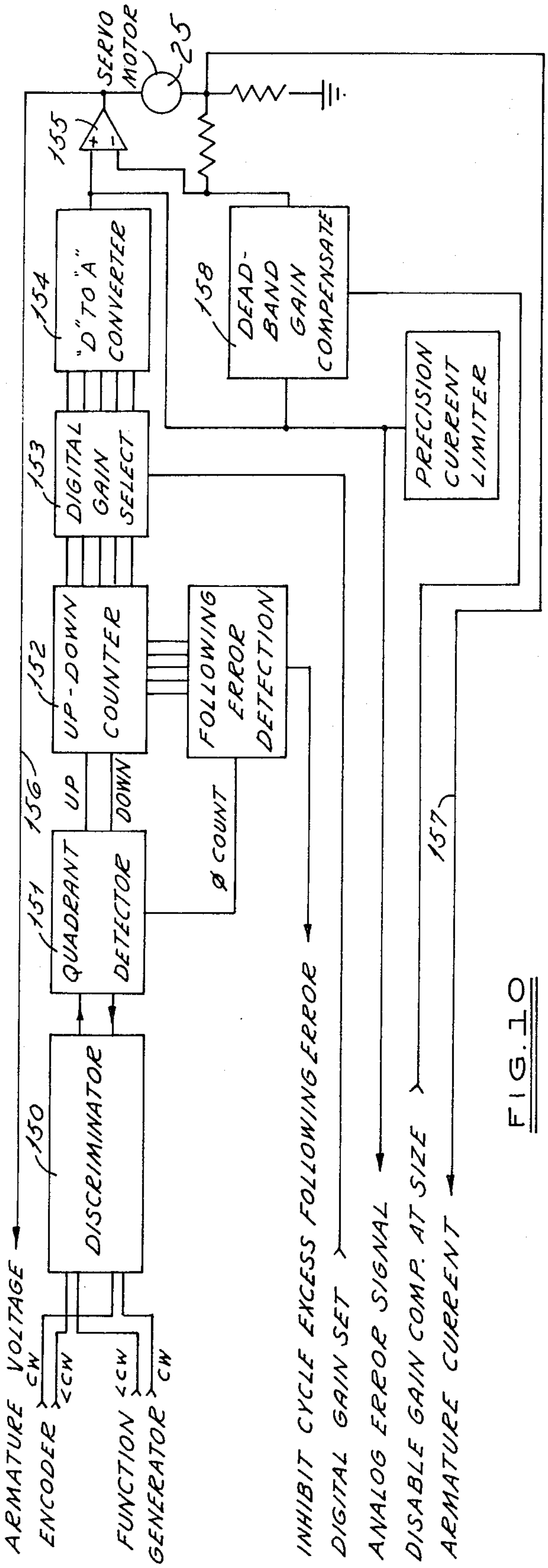
ARMATURE VOLTAGE
ENCODER
CW
CCW
FUNCTION GENERATOR
DISCRIMINATOR
150
QUADRANT DETECTOR
151
UP
DOWN
156
UP-DOWN COUNTER
152
∅ COUNT
FOLLOWING ERROR DETECTION
DIGITAL GAIN SELECT
153
"D" TO "A" CONVERTER
154
155
SERVO MOTOR
25
DEAD-BAND GAIN COMPENSATE
158
PRECISION CURRENT LIMITER
INHIBIT CYCLE EXCESS FOLLOWING ERROR
DIGITAL GAIN SET
ANALOG ERROR SIGNAL
DISABLE GAIN COMP. AT SIZE
ARMATURE CURRENT
157

FIG. 10

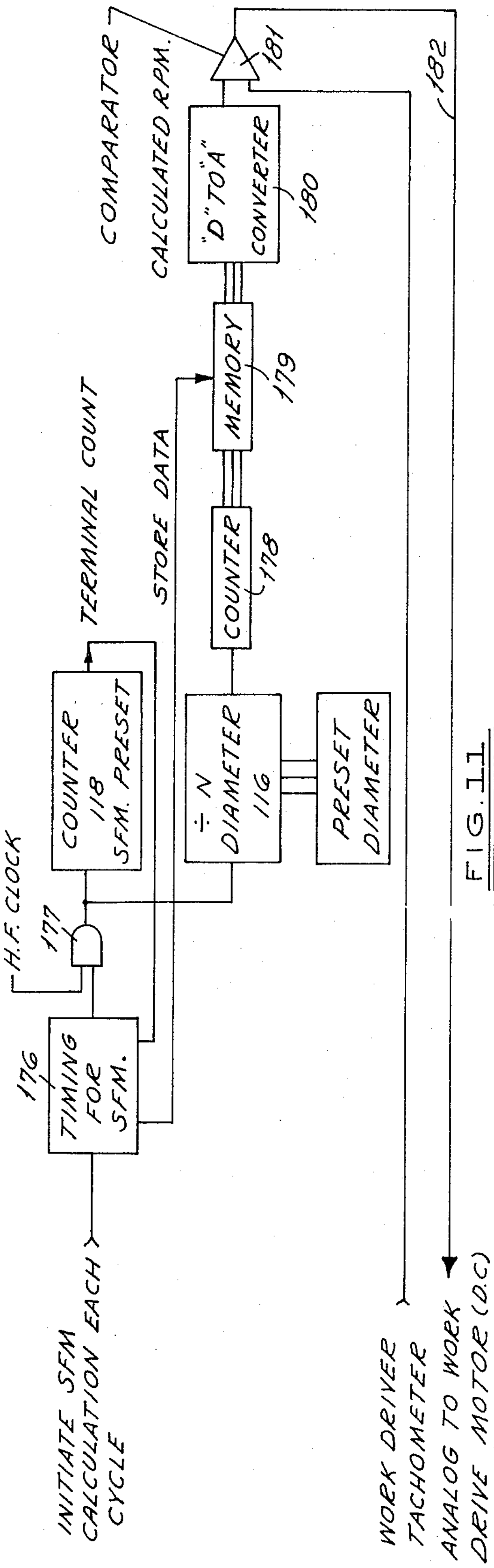
INITIATE SFM CALCULATION EACH CYCLE
TIMING FOR SFM.
176
H.F. CLOCK
177
COUNTER 118 SFM. PRESET
TERMINAL COUNT
÷ N DIAMETER 116
PRESET DIAMETER
STORE DATA
COUNTER
178
MEMORY
179
"D" TO "A" CONVERTER
180
CALCULATED RPM.
COMPARATOR
181
182
WORK DRIVER TACHOMETER
ANALOG TO WORK DRIVE MOTOR (D.C)

FIG. 11

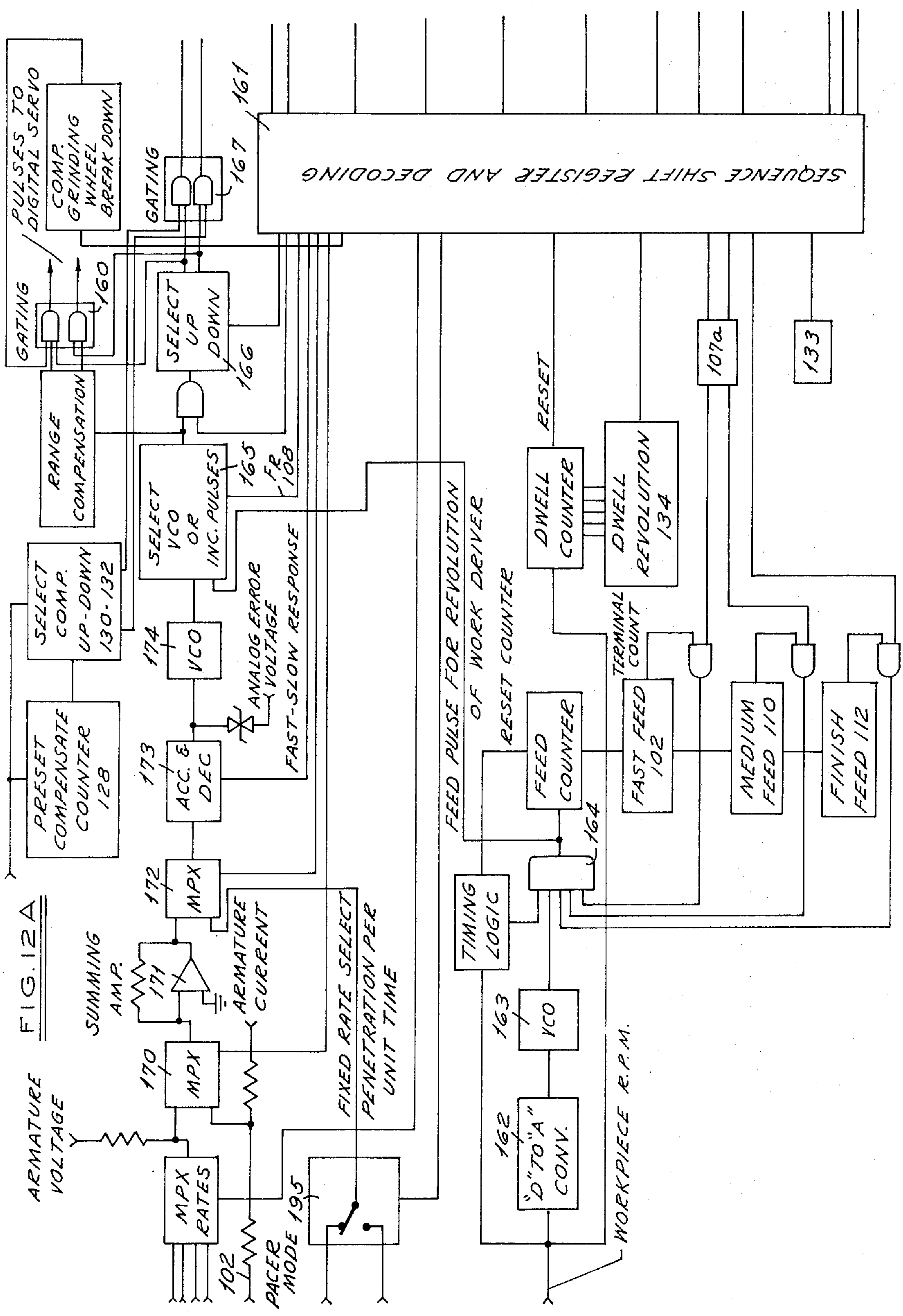
PULSES TO DIGITAL SERVO
COMP. GRINDING WHEEL BREAK DOWN
GATING
GATING
160
167
161
SEQUENCE SHIFT REGISTER AND DECODING
SELECT UP DOWN
166
RANGE COMPENSATION
SELECT VCO OR INC. PULSES
165
FR 108
SELECT COMP. UP-DOWN 130-132
PRESET COMPENSATE COUNTER 128
174
VCO
ANALOG ERROR VOLTAGE
FAST-SLOW RESPONSE
173
ACC. & DEC
172
MPX
SUMMING AMP.
171
ARMATURE CURRENT
170
MPX
ARMATURE VOLTAGE
MPX RATES
102
PACER MODE 195
FIXED RATE SELECT
PENETRATION PER UNIT TIME
FEED PULSE FOR REVOLUTION OF WORK DRIVER
RESET COUNTER
TIMING LOGIC
163
VCO
162
"D" TO "A" CONV.
WORKPIECE R.P.M.
FEED COUNTER
164
RESET
DWELL COUNTER
DWELL REVOLUTION 134
TERMINAL COUNT
FAST FEED 102
MEDIUM FEED 110
FINISH FEED 112
107a
133

FIG. 12A

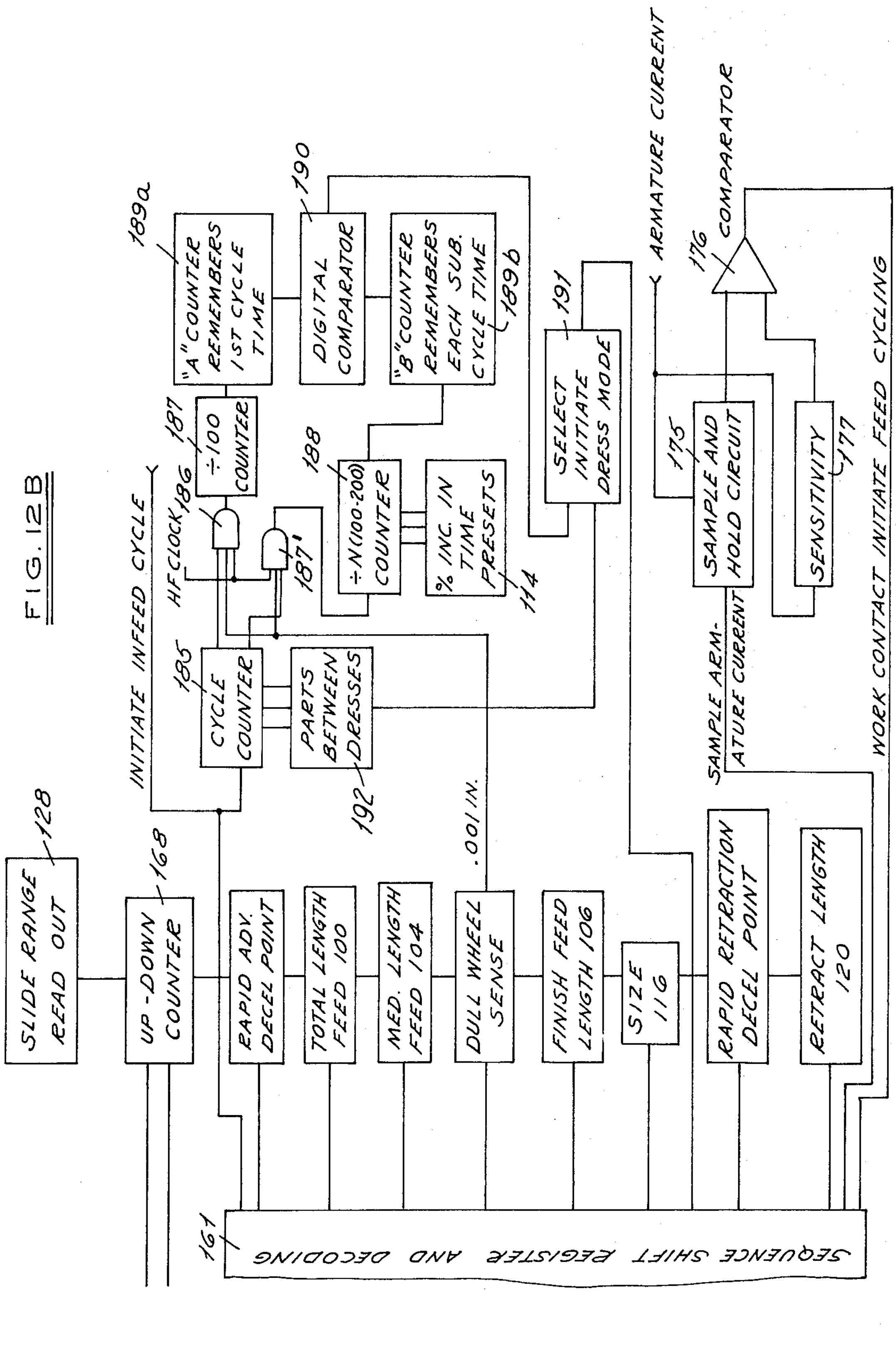
SLIDE RANGE READ OUT
128
UP-DOWN COUNTER
168
RAPID ADV. DECEL POINT
TOTAL LENGTH FEED 100
MED. LENGTH FEED 104
DULL WHEEL SENSE
.001 IN.
FINISH FEED LENGTH 106
SIZE 116
RAPID RETRACTION DECEL POINT
RETRACT LENGTH 120
SEQUENCE SHIFT REGISTER AND DECODING
161
INITIATE INFEED CYCLE
CYCLE COUNTER
185
PARTS BETWEEN DRESSES
192
HF CLOCK
186
187
187'
÷100 COUNTER
"A" COUNTER REMEMBERS 1ST CYCLE TIME
189a
DIGITAL COMPARATOR
190
"B" COUNTER REMEMBERS EACH SUB. CYCLE TIME
189b
÷N(100-200) COUNTER
188
% INC. IN TIME PRESETS
114
SELECT INITIATE DRESS MODE
191
ARMATURE CURRENT
COMPARATOR
176
SAMPLE AND HOLD CIRCUIT
175
SENSITIVITY
177
SAMPLE ARMATURE CURRENT
WORK CONTACT INITIATE FEED CYCLING

FIG. 12B

GRINDING MACHINE

This invention relates to grinding machines and particularly to a method and apparatus for producing precise relative movement between a workpiece and a machine tool such as a grinding wheel.

BACKGROUND OF THE INVENTION

In machines such as grinding machines, it is conventional to rotatably support a workpiece in a appropriate manner and cause relative movement between the rotating workpiece and a rotating grinding wheel to produce accurate surfaces on the workpiece.

Two types of feed systems are commonly used commercially for causing relative movement between the workpiece and the grinding wheel and they are commonly referred to as fixed rate and force feed systems.

In the fixed rate feed system, the grinding wheel is moved a specific radial distance, typically a fraction of a thousandth to a few thousandths of an inch, for each rotation of the workpiece. Various means have been used for producing the fixed feed rate. One common method is to drive the support for the grinding wheel by means of a screw which itself is driven by a stepping motor. The fixed feed rate is then determined by controlling the number of stepping pulses in relation to the revolutions per unit time of the workpiece.

In the force feed system, the grinding wheel is moved with respect to the workpiece with a constant force. One common type force feed system comprises the use of a hydraulic actuator for moving the support or slide for the grinding wheel. The pressure supplied to the hydraulic actuator is maintained at a constant predetermined value by an appropriate pressure control device resulting in a constant force exerted on the support for the gringing wheel. The constant force exerted by the hydraulic actuator does not always insure constant force of the grinding wheel against the workpiece because of the friction that is involved in moving the support. Accordingly, various low friction devices have been used such as hydrostatic slides and the like to reduce the friction.

Although fixed rate feed systems have received wide acceptance and are often satisfactory, there are certain disadvantages in present commercially available fixed rate feed systems. One disadvantage is that since the hardness of successive parts or workpieces in a production run may differ, the optimum feed rate is greater for softer than for harder material. Thus, it may be that the wheel is driven at a rate faster than the optimum because of the variation in hardness of the workpieces. It has been conventional to adjust the feed rate for the hardest material anticipated. As a result, the softer workpieces are ground at a slower rate than optimum with a consequent waste of time and possible reduction in the quality of the grinding operation. Another disadvantage of a constant or fixed feed rate system is that some additional system must be provided for rapid traverse of the grinding wheel up to the point where the wheel first makes contact with the workpiece. Otherwise, there is a substantial loss in time. If the workpieces vary in size, the feed rate must be established at a nominal size to accommodate the largest workpieces resulting in a loss of valuable time due to the relatively slow movement at the constant feed rate before any actual contact with the workpiece occurs.

Experience has indicated that if the range of hardness varies substantially, optimum feed rate can be achieved by using aconstant force feed system. The use of such a constant force feed system results in a feed rate which will be slower for harder material and faster for softer material. If the preset force is accurately established by experience, the feed rate will be substantially optimum for a practical range of hardnesses. This will result in high production because the softer pieces are cut faster and the harder pieces are produced at a slower rate with acceptable finish quality. Furthermore, by utilizing a constant feed force, workpieces of varying initial diameters or sizes can be accommodated by a deceleration from the traverse rate to a nominal feed rate. The nominal feed rate can be set somewhat higher than the highest feed rate to be used in actual cutting. Thus, the grinding wheel can be advanced more rapidly until contact with the workpiece is established. Then, the constant force feed rate automatically reduces the feed rate to the optimum for the hardness of the workpice being worked upon.

However, there is a problem with respect to constant force feed systems in that if a workpiece is eccentric, the high side of the workpiece tends to push the grinding wheel back against the constant force due to the high compliance of the hydraulic system used. The push back of the grinding wheel merely diverts more fluid through the pressure control device while still maintaining constant force and the grinding wheel continues to cut all around the workpiece to the desired depth per turn but does not clean up the eccentricity.

Thus, in one type of system that has heretofore been proposed, a constant force feed is established by a hydrualic actuator or the like until the final finish grinding during which a stepper motor is utilized to produce a constant rate feed in an effort to remove the eccentricity.

One of the problems with respect to the use of a stepper motor in both constant rate feed and constant force feed is that the rate of pulse transmission is depended upon to establish the rate of grinding wheel movement and the number of pulses transmitted is counted and is utilized to determine the distance traveled. However, fluctuations in loading can result in overloading of the stepper motor so that some or all of the pulses fail to produce the intended motion. In such cases, either or both the distance and the rate may be different from that which was intended.

Another problem with respect to prior grinding machines relates to the manner of determining when the grinding wheel should be dressed. One method that has been suggested is to sense the actual wear of the wheel and then dress the wheel when the wear exceeds a predetermined amount. Another method comprises dressing the wheel after a predetermined number of cycles. The proper and timely dressing of the wheel is particularly important in connection with constant force grinding systems since a dull wheel will result in inefficient grinding from the standpoint of time and surface finish.

Another problem with respect to prior grinding machines relates to speed of rotation of the workpiece. Conventionally, the operator must calculate the desired speed of rotation from the diameter of the workpiece and the desired surface speed (S.F.M.). This necessitates a separate calculation for each diameter and surface speed to be used.

Accordingly, among the objects of the invention are to provide a grinding machine wherein relative movement between the workpiece and the grinding wheel can be produced either at a fixed rate, at a constant force feed, or any desired combination of both; wherein in either mode, the eccentricity of the workpiece is removed; wherein the movement in the force feed mode is controlled to remove eccentricity; wherein both rapid traverse and extremely slow feed rates are achieved by a single prime mover; wherein the disadvantages of the use of a stepper motor are avoided; wherein a signal for wheel dressing and wheel wear is produced without calculation on the part of the machine operator; wherein the movement of the grinding wheel relative to the workpiece is maximized in terms of time so that the optimum time is involved; wherein the machine accommodates for diameter of the workpiece and desired cutting speed without calculation by the operator.

SUMMARY OF THE INVENTION

A grinding machine wherein the grinding wheel is moved relative to the workpiece by a screw that is rotated by an electric motor that produces a torque that is proportional to the current applied thereto. The movement of the grinding wheel is controlled in a constant force or a constant rate mode.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is an exploded perspective view of a grinding machine embodying the invention.

FIG. 2 is a side elevational view of a grinding machine embodying the invention.

FIG. 3 is a fragmentary sectional view taken along the line 3—3 in FIG. 2.

FIG. 4 is a graph to the torque-current characteristic of a motor utilized in the machine.

FIG. 5 is a graph of the torque-current characteristic as modified for use in the machine.

FIG. 6 is a cycle chart for one mode of operation.

FIG. 7 is a cycle chart for another mode of operation.

FIG. 8 is a plan view of a control panel utilized in the machine.

FIG. 9 is a time chart of R.P.M. and motor current during the operation of the machine.

FIG. 10 is a schamatic of a portion of the electronic circuitry.

FIG. 11 is a schematic of another portion of the electronic circuitry.

FIGS. 12A and 12B are portions of a schematic of another portion of the electronic circuitry.

DESCRIPTION

Referring to FIGS. 1–3, the invention is shown as applied to a grinding machine comprising a base 10 with a table 11 thereon on which a workpiece W is rotatably supported by an appropriate mandrel 12 and rotated by a motor 13. The table 11 may be reciprocated by appropriate mechanism (not shown). The machine further comprises a main slide 14 and a cross slide 15 on which a grinding wheel G is rotatably mounted and driven by a motor 16.

The main slide 14 is supported on the base 10 by hydrostatic bearings such as disclosed in the U.S. Pat. to Porath No. 3,231,319, issued Jan. 25, 1966. The cross slide 15 is, in turn, supported on the main slide 14 by similar hydrostatic bearings. Slide 14 can be reciprocated on base 10 by a suitable mechanism (not shown).

A screw 20 is rotatably mounted by ball bearings 21 on the main slide 14. A nut 22 of the ball bearing type is mounted on the screw 20 and connected to the cross slide 15 by integral flanges 23. Torque for turning the screw 20 is provided at one or both ends by electric motors 25 of the precision torque type. More specifically, the available torque from a motor of this type is accurately proportional to the value of current flowing in its windings at any given time, as shown in the graph, FIG. 4. Such motors are usually provided with permanent magnetic fields and are adapted to be energized by direct current. Thus, by adjustment of the current in the motors 25, the torque applied to the screw 20 may be accurately controlled.

If the screw were rotated without friction in its end bearings and in the nut, the torque produced by the motors would be convertible without loss of proportional force on the cross slide 15. In such case, the frictionless screw drive would be reversible, that is, reactive force on the slide would, if sufficient, cause reverse rotation of the motors. In such an arrangement, an eccentric workpiece could be ground at constant feed force but with no correction of the eccentricity.

In accordance with the invention, the bearings 21 supporting the ends of the screw 20 are deliberately preloaded to provide a carefully controlled constant frictional resistance to rotation of the screw 20. This frictional resistance is adjusted to a value just above the threshold of reversibility so that the friction is high enough to prevent rotation of the screw 20 by a force on the cross slide 15. Any conventional means can be used for preloading the bearings 21.

Further, in accordance with the invention, a constant minimum forward-driving current is provided for the motors 25 such that the constant screw friction is equalized. Then, by adding a forward-driving current, a proportional force is provided for the slide 15. This is shown in the graph in FIG. 4. By this arrangement, the constant friction load on the screw is overcome by the constant minimum forward-driving current and any additional forward-driving current produces the desired proportional force of the slide 15.

For example, a deliberately provided friction of 1 lb.-ft. can be provided on the screw 20. A constant basic current in each of the motors may be 4 amperes which is sufficient to produce 1 lb.-ft. torque. Each additional ampere to the two motors produces a total of 0.25 lb.-ft. of torque. With a fixed or tare friction cancelled out by the constant basic 4 amperes, any additional current produces proportional torque which is transmitted to the table. As indicated above, the hydrostatic construction of the slide and table produces as essentially frictionless relationship which will not impede movement of the grinding wheel by the motors.

Further, in accordance with the invention, an encoder or pulse generator 26 is provided on the end of the screw 20. The encoder 26 includes a housing fixed to slide 14 and a rotatable member fixed to screw 20. A typical encoder comprises a pulse generator of the optical-electronic type having a very high resolution on the order of 20,000 pulses per revolution of the shaft. Thus, in a screw having a thread lead of 0.2 inch per revolution, a travel of 0.000010 inch can be obtained for each pulse generated.

This relationship can be summarized as follows:

Feed screw lead 0.200 inch

One revolution equals 20,000 pulses

One pulse equals 0.000010 inch

As presently described, by means of electronic elements including a high speed counter, the pulses from the generator **26** can be totaled over a period and used to record distance of slide travel. Other electronic elements perform a differentiation with respect to time which delivers a signal representing the rate of pulses per second from the generator. Pulses per second can be scaled by the electronic circuitry to represent inches per minute (or per second) of slide travel rate. Thus, using the pulse generator **26** and its associated electronic circuitry, it is possible to have available signals representing the position of the slide **15** and the rate of motion of the slide **15**.

These rate and position signals can be used not only for indication but also for control. In the case of position, a predetermined pulse count value can be entered at the start of a segment or portion of slide motion. When a pulse count has been accumulated from the encoder **26** that matches the preset value, the segment of motion will be terminated by stopping or changing speed of the drive motors. Likewise, speed of slide motion may be controlled by presetting a signal representing the desired speed. This signal is compared with the pulse rate from the encoder **26** and the voltage to the motors is automatically adjusted until the pulse rate matches the preset value.

It is to be noted that the available torque produced by a D.C. motor is determined by the value of current flowing (as previously mentioned) while the speed of the motor is controlled by the voltage applied. As is well known, these two quantities are interrelated and they cannot both be independently controlled at the same time. However, either can be regulated to suit a condition and the other will automatically assume a consistent value. In the following description, there will be situations in which the torque value is significant. In such cases, the current flow is controlled while the voltage and speed conform. In other situations, speed control is paramount. In those cases, the voltage is controlled while the current and torque conform.

The use of the above design for both position and speed make the apparatus embodying the invention exceptionally versatile and positive. Using the feed-back encoder or pulse generator assures that only actual motion of the screw produces pulses which are interpreted for speed and distance.

A typical pulse generator is of the type manufactured by Baldwin Electronics Inc., Little Rock, Ark., and designated Model 5V671D Optical Increment Encoder with a maximum frequency response of outputs 200 KHz.

The modes or manners in which the apparatus embodying the invention can be used are shown in the cycle charts, FIGS. **6** and **7**. As shown in FIG. **6**, the fixed feed rate mode comprises an overall range with a rapid traverse range that can be varied. Within the rapid traverse range, there is a total feed for grinding. Just prior to the beginning of the total feed, there is a deceleration. Upon contact with the workpiece, the total feed is initiated. The total feed, in turn, is divided into a fast feed that can be varied both in rate and length, a medium feed that can be varied both in rate and length, and a finish feed that can be varied both in rate or length.

The grinding machine can also be operated in a different mode analogous to a constant force feed but since it has definite advantages over conventional constant force feed, it is herein designated as a feed paper mode. As shown in FIG. **7**, in the feed pacer mode, there is an overall range, a variable rapid traverse range, and a total feed range divided into a fast feed and finish feed of variable force and length and variable rate and length within the total feed range. As in the case of the fixed feed rate, there is a deceleration and upon contact with the workpiece, the fast feed is initiated. In addition, as presently described, there is a dull wheel sensing which occurs just prior to the finish feed.

Also, in both modes, the optimum workpiece rate of rotation is always utilized.

A control panel for the grinding machine is shown in FIG. **8** and comprises a plurality of push button switches having the following designations:

WORKHEAD CONTINUOUS
WORKHEAD AUTO
SLIDE RETRACT
DRESS CYCLE
SINGLE CYCLE
START
AUTO
STOP
LOAD
UNLOAD
CHUCK
DE-CHUCK
FEED PACER (F_P)
FIXED FEED (F_R)
IN
OUT
PLUS
MINUS

In addition, the panel includes thumb wheel switches for the following selections:

RETRACT LENGTH
TOTAL FEED LENGTH
MEDIUM FEED LENGTH
FINISH FEED LENGTH
FEED RATE - FEED FORCE
MEDIUM FEED RATE
FINISH FEED RATE
DRESS AMOUNT/PASSES
DRESS CYCLE COUNT
WHEEL SENSOR TIME/INCREASE %
DWELL REVOLUTIONS
SLIDE RANGE
SIZE COMPENSATOR
WORK S.F.M.
WORK DIAMETER

In both charts, FIGS. **6** and **7**, the zero position at the right represents the position of the grinding wheel when it is full advanced and its cutting operation is completed. Thus, all other positions on the charts are reckoned back from final finish depth. It may be noted that positions marked on the charts are not scaled to be pictorially representative of actual relative locations.

In both charts, the full length is designated range and is indicated as 10 inches long, as an example. The range is the full travel capacity of the feed slide screw. This provides, amon other things, for changing wheels, maintenance work, etc.

In both charts, the distance from zero to the start of rapid traverse is given as 4 inches, for example. This distance can be less than the maximum, as more fully described below.

The start point for rapid traverse is the normal parking location for the wheel slide between workpieces and allows clearance for loading pieces, manual gauging, etc. Rapid traverse itself is forward slide motion at a speed many times greater than any feed rate. This speed is automatically controlled by a factory-set signal which is compared with the generated pulse rate, as aforesaid. The purpose of rapid traverse is to move the wheel quickly from the parking position to a position just before contact with the work.

The distance marked total feed in both charts is the distance from zero to (or just outside of) first contact with the work. This distance depends upon the total amount of the stock to be removed from the workpiece and is determined by the machine operator who sets in the amount by means of the digital thumbwheel switch designated **100** in FIG. **8.**

The distance from the start of rapid traverse is controlled by counting pulses from the start of rapid traverse to the preset start of total feed length. This is an automatic function of the electronic circuitry.

As indicated on both charts, the slow down from rapid traverse to feed rate occurs over a distance of 0.100 inch preceding the start of the total feed segment. The distance from start of rapid traverse to the start of the deceleration interval is controlled by pulse count. The position for the start of deceleration is always 0.100 inch ahead of the start of total feed and is automatically shifted by the setting of switch **100.**

As presently described, the electronic control circuitry includes elements which use accumulated pulse counts conjointly with the pulse rate to change the desired pulse rate progressively during the slow down.

Fast feed is an interval within the total feed interval. In the fixed rate chart of FIG. **6,** it extends to the start of medium feed. During this interval, the wheel advances at fixed feed rate using the pulse rate from generator **26** as the control signal, as previously explained. The criterion for this feed rate is set by the operator by means of thumbwheel switch **102** shown in FIG. **8.** The distance traveled at fast feed is determined by pulse count up to the accumulated total set by the operator on switch **104** as the start of medium feed. The medium feed interval extends to the start finish feed and terminates when the pulse count matches that set on switch **106** (FIG. **8**).

The fast feed for the pacer mode of FIG. **7** is executed under the conditions for force feed as explained previously herein. However, the maximum feed rate during this interval is controlled by the pulse rate and the criterion is set on switch **102** (FIG. **8**) just as was the fast fixed rate referred to in FIG. **6.** The difference is that the setting of switch **102** is an actual fixed feed rate for the fixed feed mode of FIG. **6** while it is merely a maximum force for the pacer feed mode of FIG. **7.** The actual feed rate for the feed pacer mode (FIG. **7**) is set by the current in motor(s) **25** and depends upon the hardness of the material being ground. The term "pacer rate" means that the slide is prevented from lunging ahead due to gaps or eccentricities.

Obviously, it is necessary to furnish a control signal to determine whether the control during fast feed is to be at a fixed rate (controlled by pulse rate) or at a rate determined by hardness (controlled by motor current and limited only by pulse rate). This selection signal is provided by the push button switches **107** and **108.** If switch **107** is pressed, the feed pacer mode is selected and the feed rate is determined by work hardness. If switch **108** is pressed, the fixed rate mode is selected and the feed rate is controlled strictly by pulse count.

In the fixed rate mode of grinding, it is conventional to start the grinding at a relatively high feed rate and then reduce it for improvement of surface finish and other reasons. FIG. **6** shows a medium feed interval defined, by accumulation of pulse counts, between the start of medium feed and the start of finish feed. The feed rate in this interval is controlled by pulse rate and the criterion is set on switch **110.** No medium feed interval is shown on FIG. **7** because the force feed principle is used for the whole grinding operation except for the finish feed, as described below. Thus, in the feed pacer mode, the setting of switches **104, 110** is not effective.

It is known that highest accuracy of roundness and the best surface finish require that the very last thin layer (fraction of a thousandth of an inch) be removed using a very low fixed feed rate. Thus, the finish feed interval in both the fixed feed mode and the feed pacer mode is executed at a fixed feed rate. The rate is controlled by pulse rate and the distance by pulse count. The distance is set on switch **106** and the rate on switch **112.** Either mode of operation uses these settings.

As previously described, the feed rate under force or pacer feed is basically determined by the hardness of the workpiece. However, it is a necessary corrolary that this rate is also affected by the sharpness (presence of fresh particles and lack of glaze) of the wheel. For a given hardness of work, a sharp wheel will feed faster than a dull wheel under fixed force.

Assuming a relatively small span of hardness from piece to piece (or a random mix of hardness from piece to piece), progressive reduction of feed rate, under fixed force, will occur as the wheel becomes duller due to use. In the feed pacer mode, the time for a predetermined movement of the grinding wheel at a portion of the cycle is compared with a predetermined time an a dressing signal is produced when the current time exceeds the predetermined setting. More specifically, the operator inserts a percentage in switch **114** which is representative of the relationship between the time of travel over a specific distance for a newly dressed wheel versus one that required dressing. In the circuitry, the pulses produced by encoder **26** during the 0.001 inch just before the starting point of the finish feed interval are counted and the time for that set of pulses is determined in micro-seconds and this time is visually recorded on the dial of switch **114** for each piece ground. From these two values, the current rate of feed is determined. This current feed rate is automatically compared with a previously determined rate in terms of good pieces and economical production rate. A certain percentage decrease in feed rate, due to wheel dulling, is dialed in on switch **114.** When this change is reached, the piece in process is finished but an automatic dressing operation is initiated to sharpen the wheel before the next piece is ground.

When the pulse count indicates that the wheel has progressed to the point marked zero in either chart, the proper size has been reached. It is necessary, however, to hold that position for a predetermined number of work revolutions to assure a clean finish. This hold or dwell time, in seconds, will vary according to the diameter and speed of revolution of the work. It has heretofore been common for the operator to calculate a dwell time based upon diameter of the workpiece and surface speed per minute and to make a time setting in the machine. In accordance with this invention, the operator sets switch **134** to the desired dwell revolutions and the electronic circuitry will automatically determine and control the dwell for the desired number of revolutions, taking into consideration the diameter and surface speed settings of switches **116, 118.**

Upon completion of the dwell, in either mode, a signal is given to reverse the motor(s) **25** at rapid traverse rate. The slide retracts to its parking posiion. The distance to the parking position is controlled by pulse count. As before mentioned, the distance to parking position is shown as 4 inches in the example. However, a different retraction distance can be preset on switch **120.**

Machine Set-Up

Returning to FIGS. **6** and **7**, it is recalled that the full range of wheel slide travel is 10 inches in the example. The movement of the slide outward beyond the starting position for rapid traverse is controlled by pushbuttons **122** in (toward zero in FIGS. **6** and **7**) and **124** for out. The position of the slide throughout its range is indicated, by way of pulse counting, on the digital readout device **126.**

When a new type of workpiece is to be ground, a sample is put in place and the desired diameter and surface feet per minute are dialed in on the switches **116** and **118.** This causes the sample workpiece to be rotated at the proper revolutions per minute, as explained above. Also, the various distances and rates are dialed in switches **120, 100, 104, 106, 102, 110, 112.**

Now the grinding wheel is caused to approach the work by pressing the button **122.** This button causes the wheel to advance faster the further in it is pressed. A typical button comprises a slide actuated potentiometer that produces a progressively changing voltage and upon being fully depressed actuates a micro switch producing a maximum voltage. Thus, the operator can cause fast approach to the work and then manually reduce the speed for set-up grinding.

The sample piece is thus ground under manual control until it cleans up, that is, until all irregularities or eccentricities are removed and a true cylinder is being ground. At that time, the wheel is manually withdrawn (pushbutton **133**) to the extent of the setting of retraction length on switch **120.** Next, the part is gauged for diameter. This gauging may be manual or, in more advanced embodiments, by automatic gauging devices.

In the original description of FIGS. **6** and **7** above, it was asserted that the zero end represents the slide position for a finish piece. Therefore, if the cleaned up sample is found to be of proper diameter, it means that the slide reached (and did not pass) zero position. If the sample is found to be too large (assuming O.D.) it means the wheel did not reach zero position and should go further when a production piece is to be made under automatic control. This is equivalent to moving the zero end of the cycle in FIGS. **6** and **7** to the left. Conversely, if the sample is too small (still O.D.) zero should be moved to the right. It is clear that moving the zero maintains the relative positions of all distance points on the charts.

Based on the gauged sample, the operator dials in the error in diameter on the switch **128.** He then presses button **130** if the sample is too large (O.D.) or button **132** if it is too small. The effect of pressing buttons **130** or **132** is to electrically move the zero of FIGS. **5** and **6** by the amount dialed in on switch **128** so that the zero setting conforms to the zero wheel position at the end of final feed. Thereafter, all the switch settings on FIG. **8** are properly correlated to the corrected zero and proper size pieces will then be ground. Should diameter errors subsequently appear, the effective zero can be moved at any time by a new setting of switch **128** and pressing of buttons **130** or **132.**

In the early part of this description, feed rate was defined as wheel advance per revolution of the work.

In prior art machines, the feed rate is basically set in numbers which are not related to any specific relationship to the workpiece. The revolution rate of the workpiece is dependent upon its diameter and the correct peripheral speed or S.F.M. (surface feed per minute). From this calculated revolution rate, a further calculation is necessary to determine inches per minute of feed rate to get the desired inches per revolution. All these calculations are normally done manually or, at least, away from the grinding machine.

As already described, the machine of the invention provides electronic circuitry to establish the R.P.M. of the work according to dialed in diameter and S.F.M. in switches **116, 118.** As presently described, further electronic circuitry uses this work R.P.M. together with the various dialed in feed rates, in inches per revolution to set the pulse rate criteria accordingly.

Referring to FIG. **9**, the upper curve represents the variation in R.P.M. of the motor **25** which translates the grinding wheel during various portions of the cycle. As can be seen, the R.P.M. increases during the acceleration portion after which it remains constant during rapid traverse. It then decelerates to an intermediate rate during the work detection portion of the cycle. Upon contact of the work, the R.P.M. remains constant until the finish feed mode or portion of the cycle. At dwell, the R.P.M. diminishes to zero and then reverses for retraction. Simultaneously, during the various portions of the cycle, the motor current to the motors **25** changes correspondingly as is evident from the lower curve.

Electronic Circuitry

Referring to FIG. **10**, the digital servo amplifier for providing a varying voltage to the motor **25** comprises a discriminator **150** that receives pulse signals from the encoder and also from the function generator presently described. The signals from the discriminator pass to a quadrant detector **151** and, in turn, to an up-down counter **152** to a digital gain select **153** and then to a digital to analog converter **154.** The quadrant detector **151** functions to prevent the excess down pulses which occur during acceleration or deceleration from causing instability in the system. Specifically, the detector **151** operates to produce a pulse when the down count reaches zero to insure that the next pulse will be in an up direction. The analog converter **154** provides a signal to an amplifier **155** that, in turn, supplies the armature voltage through line **156** to the motor **25.** A servo motor **25** driven by the output of the amplifier **155** supplies a reading of armature current through line **157** for use as presently described. The functioning of the motor **25** to compensate for the preloading of the bearings is achieved by the use of the dead band gain compensator **158.** Compensator **158** balances out the required torque to turn the screw and the constant forward driving current so that any input signal will cause rotation of the screw. Other input and output signals are provided as labeled in FIG. **10** for use as presently described. Following error detection unit **159** functions to produce a warning or shout down signal in the event the following error is excessive. Digital gain set functions to provide for different gain in various portions of the cycle. Thus, there may be low gain to point A, then high gain to retract and then low gain during retraction. The analog error signal can be used to change the oscillator and eliminate excess following error.

Referring to FIGS. **12A** and **12B**, which are schematics of the function generator, the pulses supplied to the discriminator **150** in FIG. **10** are derived from gating **160.** The sequencing of the pulses to the gating is controlled by a sequence shift register **161** to which the inputs from the various thumbwheel switches are provided. For purposes of clarity, the inputs have been designated with the same reference numerals as in the control panel, FIG. **8.**

In the constant rate mode, the sensing of work revolutions per unit time is applied to a digital to analog converter **162** and, in turn, the analog output thereof is converted to a proportional pulse rate by a voltage controlled oscillator **163.** The rate at which the pulses are permitted to pass to the gating **160** in each portion of the cycle is controlled by the setting of the switches **102, 110, 112** and the duration thereof is controlled by the setting of the switches **100, 104, 106.** Thus, the speed and distance of the grinding wheel movement toward the workpiece is controlled. The output of a gate **164** passes to a switch **165** and, in turn, to the gating **160.** Intermediate gating including a select up-down counter **166** and gating **167** producing a reading on counter **168** that is representative of the position of the wheel with respect to the workpiece at all times. This can be provided as a readout **128.**

In the feed pacer mode, the depression of the switch **107** in the control panel (FIG. **8**) functions in the function generator (FIG. **12**) to inhibit the fast feed decode and medium feed decode shown as at **107a** in FIG. **12** so that the sequence shift register will function to control the rate of speed by the hardness, that is, by the motor current. Thus, the input of current control in the pacer mode at the left in FIG. **12** passes to a multiplexer or switch **170** which functions as a switch to a summing amplifier **171** which functions to sum the armature current and the analog voltage dialed into thumb switch **102** corresponding to the desired infeed force and transmits the different to another multiplexer **172** through an acceleration-deceleration limiter **173** and is then converted to pulses by a voltage control oscillator **174.** The pulses then pass to the gate **160** operating to apply a proportional current to the motor **25.** Thus, the rotation of the motor **25** that controls the feed is in the pacer mode limited only by the current control which, in turn, is a function of the hardness of the workpieces.

In both modes of operation, the sensing of the contact with the workpiece to change from rapid traverse to feed is achieved by sensing increase in motor current. This is designated as points A and B in FIG. **9.** The circuitry for this control is shown in the bottom portion of FIG. **12B** wherein the armature current is applied, upon signal of the shift register **161** during the last portion of the rapid traverse just prior to contact, to a sample and holding circuit **175** and is compared in a comparator **176** with an input of a setting **177.** Upon increase of the armature current beyond a predetermined amount caused by contact with the workpiece, a signal is provided by comparator **176** to the sequence shift register **161** to cause the register to shift to the next feed portion of the cycle, namely, the fast feed.

As indicated above, provision is made for controlling the rate of rotation of the workpiece. This incorporates circuitry for calculating the S.F.M. in each cycle and for making a comparison to, in turn, initiate a dressing cycle, if required. As shown in FIG. **11,** upon the beginning of each cycle, a signal is provided to a timing logic **176** which functions to trigger different signals at appropriate times as required and, in turn, to a gate **177,** to the counter, the count of which has been set by thumbwheel **118** of the control panel. The input of the preset diameter from thumbwheel switch **116** passes to a counter **178** and a memory **179** that stores the signal, then to a digital to analog converter **180** and a comparator **181.** The comparator **181** compares the signal from the tachometer driven by the work with that of converter **180** to apply a voltage through the line **182** to rotate the motor **13** that drives the workpiece W at an appropriate R.P.M. that corresponds to the diameter of the workpiece and the setting of S.F.M.

At the beginning of each cycle, a cycle counter **185** (FIG. **12B**) is initiated and functions to count infeed cycles. The output of the cycle counter **185** passes through a gate **186** and a divide counter **187** to "A" counter **189a** that functions to remember the first cycle time. Second gate **187′** functions to direct the cycle time of subsequent cycles to "B" counter. The setting of the thumbwheel switch **114** into which there has been previously provided a setting of the degree of permissible grinding wheel wear is provided to a divide counter **188** and, in turn, to B counter **189b** and then to a comparator **190** that compares the cycle time between A counter **189a** and B counter **189b** to produce a signal for initiating a dress cycle when the counts in B counter are greater than the counts in A counter. This provides a signal to a control **191** to initiate a dressing cycle. Control **191** also zeroes the "Parts Between Dress Cycle" counter **192** after the dress cycle has been completed (FIGS. **8, 12B**). More specifically, divide counter **187** can be of the divide by 100 type while divide counter **188** can be, for example, of the divide by 200 to 300 type and controlled by the setting of switch **114.** When the signals from the divide counters correspond, a dress signal is produced.

Referring further to FIG. **12A,** the inputs during work set-up from buttons **122, 124** are shown as being provided as an analog to the multiplexer **195** and pass on through the circuitry to move the zero point as determined in the aforementioned description of the cycle.

Operation - Fixed Rate Mode

Assuming that the operator has set up the machine as heretofore explained and set the electrical zero at the actual zero corresponding to the completion of the finish feed by depressing the buttons **130** or **132**, the machine is then ready for operation under either the fixed feed rate mode or the pacer feed rate mode.

Assuming that the operator has depressed button **108** corresponding to the fixed feed rate mode, he places a workpiece in the machine operating CHUCK and DECHUCK buttons and the depresses the AUTO and START buttons. The grinding wheel is then moved at the rapid traverse rate toward the workpiece with the distance traveled up to the beginning of the total feed determined by counting the pulses from the encoder. As previously explained, when the number of pulses corresponds to the movement with a predetermined distance of the beginning of total feed (0.100 inch in the example), deceleration occurs for work contact. When the pulses correspond to the number of pulses established by the switch **100**, a signal is provided to the shift register **161** to, in turn, provide a signal so that the grinding wheel will be moved at the medium feed rate set by thumbwheel switch **110**. This rate of movement will continue until the count from the encoder corresponds to the pulse count established by the setting of switch **104**. This will, in turn, cause the shift register **161** to initiate finish speed at a rate set by switch **112** and for a distance corresponding to the pulses by the setting of the switch **106**.

As previously discussed, during rapid traverse, the system provides a deceleration of the grinding wheel just prior to the beginning of the fast feed and the shift to fast feed is initiated when the current to the motor **25** during deceleration increases a predetermined amount.

After the completion of the finish feed length, the shift register **161** initiates the dwell and the dwell is continued for the number of revolutions set by switch **134**.

During each portion of the cycle under constant fixed feed rate, the movement of the grinding wheel toward the workpiece is controlled by monitoring each revolution of the workpiece and utilizing this to control the pulses at each feed rate setting. The rate set in the switches **102, 110, 112** is the precise movement of the grinding wheel toward the workpiece. Once set, the feed rates in switches **102, 110** and **112** are correct, irrespective of workpiece diameter or change in the S.F.M. settings of switches **116, 118.**

Since the feed lengths as established by switches **100, 104, 106** determine a predetermined pulse count and the grinding wheel is moved for each of the settings at the desired number of pulses as read by the encoder, the grinding wheel is moved accurately the desired distances and the disadvantages of stepper motors in losing pulses at high speeds, as discussed above, are obviated.

Operation - Modified Constant Feed or Feed Pacer Mode

Assuming that an operator has set up the machine as heretofore described and depresses the feed pacer button **107**, he may load a part in the same manner as described above. Upon depressing the START and AUTO buttons, the operation is substantially the same as described above in connection with the fixed feed rate mode except in the interval between the beginning of total feed and the beginning of finish feed. During this interval, the current to the motor **25** is monitored so that the motor drives the grinding wheel against the workpiece with the force set in switch **102.** After the completion of the fast feed portion of the feed pacer cycle, the shift register functions to shift the operation to a constant or fixed rate mode for the finish feed which corresponds to the rate set in switch **112** and the distance set in switch **106.** The finish feed thus continues in a constant or fixed rate mode for the distance set therein and then the dwell functions as in the fast rate mode.

On each cycle under feed pacer mode, just prior to the beginning of finish feed, the time for traversing a predetermined distance, indicated as 0.001 inch in the example, is compared with the time for a newly dressed wheel and when this corresponds to a predetermined percentage as set in switch **114**, a dress cycle signal is produced so that the operator will then either manually dress the wheel after completion of the cycle or the operation of an automatic dresser, such as in well known in the art, can be initiated.

In each of the modes of operation of the invention, the speed of rotation of the workpiece is always controlled in accordance with the diameter setting in switch **116** and the surface feed setting of switch **118.**

Although the invention has been described in connection with a grinding machine, various features thereof can be utilized in connection with other machine tools. Those features which relate particularly to a rotating grinding wheel are, of course, applicable to a rotating machine tool, and those features which relate to movement toward and away from a workpiece are applicable to both rotating and non-rotating machine tools. Although the application to a grinding machine has been described in connection with the manual settings on a control panel, it can be understood that where mass production of identical parts is being made, numerical or computer control can be provided.

I claim:

1. In a machine wherein a tool and a workpiece are moved relatively toward and away from each other to perform a work operation on the workpiece, the combination comprising

a first support for the tool,

a second support for the work member,

a rotatable feed member,

one of said supports being connected with said rotatable feed member such that upon rotation of said feed member, said one support is moved relative to the other support,

an electric motor connected to said feed member for rotating the same,

said motor being of the type which produces a torque that is proportional to the current applied thereto,

and an accurate resolution encoder operable to produce a large number of pulse signals for each revolution of the feed member.

2. The combination set forth in claim **1** wherein said motor is of the permanent magnet DC type.

3. The combination set forth in claim **1** wherein said feed member comprises a feed screw,

said one support which is operatively connected thereto having a nut thereon through which the screw extends, said feed screw being rotatably supported by longitudinally spaced bearings,

at least some of said bearings having a preload thereon which functions to prevent rotation of the feed screw upon a load being applied to the one support operatively connected thereto.

4. The combination set forth in claim 3 including means for applying a constant current to the motor which is sufficient to equal the preload on the feed screw such that additional current applied to the motor will produce a rotation of said feed screw proportional to the additional current.

5. The combination set forth in claim 1 including hydrostatic support means for said movable support.

6. The combination set forth in claim 1 wherein said encoder comprises a pulse generator, coupled to the feed member.

7. The combination set forth in claim 6 wherein said pulse generator comprises an optical type generator.

8. The combination set forth in claim 6 wherein said pulse generator produces pulses on the order of 20,000 pulses per revolution.

9. The combination set forth in claim 1 wherein said encoder is of the type such that each pulse is produced by movement of the support on the order of one ten-millionth of an inch.

10. The combination set forth in claim 1 including a pulse generator for producing a plurality of pulses,

and means for converting said pulses to a voltage and applying them to the motor.

11. The combination set forth in claim 1 including means for applying a predetermined voltage to said motor to rotate the motor and, in turn, move the feed member and the support connected thereto at a predetermined rate,

means for comparing the pulses received from the encoder to a predetermined count,

and means for terminating the application of voltage to said motor when the pulses from the encoder are equal to the predetermined count.

12. The combination set forth in claim 1 including means for monitoring the current being applied to the motor,

means for comparing said monitored current to a predetermined standard,

and means for controlling the current such that it does not exceed the predetermined standard.

13. The combination set forth in claim 12 including means for comparing the pulse count from the encoder to a predetermined standard,

and means for terminating the controlling of current when the pulse count equals the predetermined standard.

14. The combination set forth in claim 13 including means for applying a predetermined pulse count and a predetermined pulse rate,

means for converting said pulse rate to a voltage proportional to the rate and applying the same to the motor,

means for initiating the application of said lastmentioned pulse rate at the termination of the controlling of the current,

and means for terminating the application of said last-mentioned voltage when the pulse count from the encoder equals the predetermined pulse count.

15. The combination set forth in claim 1 including counter means for counting the pulses from the encoder and terminating the particular movement upon reaching a predetermined count.

16. The combination set forth in claim 1 including means for applying a plurality of pulses, voltage control means for converting said pulses to a count and applying them to the motor, and means for comparing the rate of said pulses from the encoder to a predetermined standard rate and permitting the passage of pulses therefrom to the voltage control means only at a predetermined maximum rate not exceeding said standard.

17. The combination set forth in claim 1 including control means for said motor comprising means for establishing a predetermined pulse rate and predetermined number of counts for each of the portions of desired movement of the support,

means for converting each said pulse rate to a voltage,

and means for controlling the application of each said voltage to the motor to provide a movement of said one support in each of the predetermined rates and distances corresponding to the predetermined number of counts.

18. The combination set forth in claim 17 wherein said portions of movement comprise a total feed length,

a rapid traverse length.

19. The combination set forth in claim 18 wherein the total feed length is further divided into fast feed, medium feed and finish feed portions, each of which has means for varying the rate and length thereof.

20. The combination set forth in claim 18 wherein the total feed is divided into fast feed and finish feed portions,

means for limiting the current applied to the motor to a predetermined value during the fast feed portion,

and means for limiting the duration of said last-mentioned current applied to the motor,

the finish feed portion having means for varying the rate and length of feed of pulses to the means for controlling the motor.

21. The combination set forth in claim 20 including means for comparing the current applied to the motor to a predetermined standard and means for limiting the current to the motor such that it does not exceed the predetermined standard.

22. The combination set forth in claim 21 including means responsive to the termination of the fast feed portion for supplying a predetermined rate of pulses during the finish feed portions and means for converting said rate of pulses to a voltage proportional to said rate and applying it to said motor.

23. The combination set forth in claim 1 including means for measuring the duration of a predetermined portion of the movement of the workpiece,

and means responsive to a predetermined change in this duration to produce a signal.

24. The combination set forth in claim 1 including means for controlling the speed of the workpiece comprising means manually programmable for the diameter and S.F.M. of the workpiece and means responsive to said last-mentioned means for varying the speed of the workpiece such that the workpiece rotates at the predetermined S.F.M.

25. The combination set forth in claim 1 including means responsive to a predetermined increase of current to the motor upon engagement of the tool with the workpiece to cause a signal changing the rate of movement of the grinding wheel relative to the workpiece.

26. The combination set forth in claim 25 wherein said engagement of the workpiece is operable to cause means for controlling the current delivered to the motor to become operable.

27. The combination set forth in claim 1 including means responsive to the revolutions of the workpiece per unit time for controlling the rate of a series of pulses,

and means for producing a voltage proportional to the rate of the pulses and applying said voltage to the motor.

28. The combination set forth in claim 1 including means responsive to the diameter of the workpiece and a predetermined peripheral surface speed of the tool with respect to the workpiece for controlling the speed of rotation of the workpiece to produce said predetermined surface speed.

29. The combination set forth in claim 1 including means for periodically sensing the time interval for movement of the tool relative to the workpiece through a predetermined distance,

means for comparing said time with a predetermined time interval,

and means for producing a signal when said sensed time interval exceeds said predetermined time interval.

30. The combination set forth in claim 1 including means manually programmable for a predetermined desired diameter of the workpiece, a predetermined surface speed per minute and a predetermined number of revolutions of the workpiece for rotating the workpiece for a predetermined number of revolutions.

31. The combination set forth in claim 1 including means for sensing the time required for the removal of a predetermined amount of material from the workpiece,

and means for producing a signal when said time deviates from a predetermined standard by a predetermined percentage.

32. The combination set forth in claim 1 including means for measuring and storing the time for removal of a first predetermined portion of the workpiece,

means thereafter successively measuring the time for removal of an equivalent portion of the workpiece on each successive cycle,

and means for producing a signal when said any of said successive times exceeds the first-mentioned time by a predetermined percentage.

33. In a grinding machine wherein a rotating grinding wheel and a workpiece are moved relatively toward and away from each other to perform a work operation on the workpiece, the combination comprising

a first support for the grinding wheel,

a second support for the work member,

a rotatable feed device,

said first support being directly connected with said rotatable feed device such that upon rotation of said feed device, said first support is moved relative to said second support,

an electric motor directly connected to said feed device,

said motor being of the type which produces a torque that is proportional to the current applied thereto,

and an accurate resolution encoder directly connected to the feed member and operable to produce a plurality of signals of predetermined duration for each revolution of the feed member.

34. The combination set forth in claim 33 wherein said motor is of the permanent magnet DC type.

35. The combination set forth in claim 33 wherein said feed member comprises a feed screw,

said first support which is operatively connected thereto having a nut thereon through which the screw extends,

said feed screw being supported by longitudinally spaced bearings,

at least some of said bearings having a preload thereon which functions to prevent rotation of the feed screw upon a load being applied to the support connected thereto.

36. The combination set forth in claim 33 including means for applying a constant current to the motor which is sufficient to equal the preload on the feed screw such that additional current supplied to the motor will produce a rotation of said feed screw proportional to the additional current.

37. The combination set forth in claim 33 including hydrostatic support means for said movable support.

38. The combination set forth in claim 33 wherein said encoder comprises a pulse generator, coupled to the feed member.

39. The combination set forth in claim 38 wherein said pulse generator comprises an optical type generator.

40. The combination set forth in claim 38 wherein said pulse generator produces pulses on the order of 20,000 pulses per revolution.

41. The combination set forth in claim 33 wherein said encoder is of the type such that each pulse is produced by movement of the support on the order of one ten-millionth of an inch.

42. The combination set forth in claim 33 including a pulse generator for producing a plurality of pulses,

means for converting said pulses to a voltage applying them to the motor.

43. The combination set forth in claim 42 including means for reducing the voltage to the motor just prior to contact between the workpiece and the grinding wheel,

means for monitoring the current of the motor during a portion of said last-mentioned monitoring,

and means for initiating the last succeeding portion of the cycle when the percentage increase in current exceeds a predetermined amount.

44. The combination set forth in claim 33 including means responsive to a predetermined diameter and predetermined speed for maintaining the relative positions of the workpiece and grinding wheel for a predetermined number of revolutions at the completion of the movement of the grinding wheel and workpiece relative toward one another.

45. The combination set forth in claim 33 including means for controlling the speed of the workpiece comprising means programmable for the diameter and SFM of the workpiece and means for varying the speed of the workpiece such that the workpiece rotates at the predetermined SFM.

46. The combination set forth in claim 33 including means responsive to a predetermined increase of current upon engagement of the grinding wheel with the workpiece to cause a signal changing the rate of movement of the grinding wheel toward the workpiece.

47. The combination set forth in claim 46 wherein said engagement of the workpiece is operable to cause means for controlling the current delivered to the motor to become operable and thereby limit the movement of the grinding wheel toward the workpiece.

48. In a grinding machine wherein a rotating grinding wheel and a workpiece are moved relatively toward and away from each other to perform a work operation on the workpiece, the combination comprising

a first support for the grinding wheel,
a second support for the work member,
a rotatable feed screw,
said first support being connected with said feed screw such that upon rotation of said feed screw, said first support is moved relative to said second support,
said support which is operatively connected to the feed screw having a nut thereon through which the screw extends,
said feed screw being supported by longitudinally spaced bearings,
at least some of said bearings having a preload thereon which functions to prevent rotation of the feed screw upon a load being applied to the support connected thereto,
an electric motor connected to said feed screw,
said motor being of the type which produces a torque that is proportional to the current applied thereto,
and an accurate resolution encoder directly connected to the feed screw operable to produce a plurality of signals of predetermined duration for each revolution of the feed screw,
means for controlling the movement of said screw and in turn said workpiece with respect to the grinding wheel through a plurality of portions of a cycle,
means for applying a predetermined rate of pulses and a predetermined number of pulses for each such portion,
and means for converting each such rate to a voltage and applying it to the motor,
means responsive to the angular rate of movement of the workpiece or controlling the rate at which the pulses are converted to a voltage and applied to the motor,
said encoder functioning to produce pulses corresponding to the movement between the workpiece and grinding wheel,
and means for terminating each portion of the cycle when the predetermined pulse count for each portion equals the pulse count from the encoder.

49. The combination set forth in claim 48 wherein said motor is of the permanent magnet DC type.

50. The combination set forth in claim 48 including means for applying a constant current to the motor which is sufficient to equal the preload on the feed screw such that additional current supplied to the motor will produce a rotation of said feed screw proportional to the additional current.

51. The combination set forth in claim 48 including hydrostatic support means for said movable support.

52. The combination set forth in claim 48 wherein said encoder comprises an optical type generator.

53. The combination set forth in claim 52 wherein said encoder produces pulses on the order of 20,000 pulses per revolution.

54. The combination set forth in claim 48 wherein said encoder is of the type such that each pulse is produced by movement of the support on the order of one ten-millionth of an inch.

55. The combination set forth in claim 48 wherein said portions of movement comprise a total feed length,

a rapid traverse length,
the latter being further divided into a total feed length.

56. The combination set forth in claim 55 wherein the total feed length is further divided into fast feed, medium feed and finish feed portions, each of which has means for varying the rate and length thereof.

57. In a grinding machine wherein a rotating grinding wheel and a workpiece are moved relatively toward and away from each other to perform a work operation on the workpiece, the combination comprising,

a first support for the gridnding wheel,
a second support for the work member,
a rotatable feed device,
said first support being directly connected with said feed screw such that upon rotation of said feed screw, said first support is moved relative to said second support,
said support which is operatively connected thereto having a nut thereon through which the screw extends,
said feed screw being supported by longitudinally spaced bearings,
at least some of said bearings having a preload thereon which funcitons to prevent rotation of the feed screw upon a load being applied to the support connected thereto,
an electric motor connected to said feed device,
said motor being of the type which produces a torque that is proportional to the current applied thereto,
and an accurate resolution encoder operable to produce a plurality of signals of predetermined duration for each revolution of the feed screw,
means for controlling the movement of said screw and, in turn, said wrkpiece workpiece respect to the grinding wheel through a plurality of portions of a cycle,
means for applying a substantially constant current to said motor during one cycle portion for maintaining said workpiece and grinding wheel in contact with a constant force,
said encoder functioning to produce pulses corresponding to the movement of the workpiece and the grinding wheel,
and means for terminating each portion of the cycle when the predetermined pulse count for each portion equals the pulse count from the encoder.

58. The combination set forth in claim 57 wherein said motor is of the permanent megnet DC type.

59. The combination set forth in claim 57 including means for applying a constant current to the motor which is sufficient to equal the preload on the feed screw such that additional current supplied to the

motor will produce a rotation of said feed screw proportional to the current.

60. The combination set forth in claim 57 including hydrostatic support means for said movable support.

61. The combination set forth in claim 57 wherein said pulse generator comprises an optical type generator.

62. The combination set forth in claim 61 wherein said pulse generator produces pulses on the order of 20,000 pulses per revolution.

63. The combination set forth in claim 57 wherein said encoder is of the type such that each pulse is produced by movement of the support on the order of one ten-millionth of an inch.

64. The combination set forth in claim 57 wherein the total feed is divided into fast feed and finish feed porrions,

the fast feed portion controlled by said means for applying a substantially constant current to the motor,

the finish feed mode having means for varying the rate and length of feed of pulses to the means for controlling the motor.

65. The combination set forth in claim 57 including means for controlling the speed of the workpiece comprising measn programmable for the diameter and SFM of the workpiece and means for varying the speed of the workpiece such that the workpiece rotates at the predetermined SFM.

66. The combination set forth in claim 57 including means responsive to a predetermined increase of current upon engagement of the grinding wheel with the workpiece to cause a signal changing the rate of movement of the grinding wheel toward the workpiece.

67. The combination set forth in claim 57 wherein said engagement of the workpiece is operable to cause means for controlling the current delivered to the motor to become operable and thereby limit the movement of the grinding wheel toward the workpiece.

68. The combination set forth in claim 57 including means for sensing the time required for the removal of a predetermined amount of material from the workpiece,

and means for producing a signal when said time deviates from a predetermined standard by a predetermined percentage.

69. The combination set forth in claim 57 including

means for measuring and storing the time for removal of a first predetermined portion of the workpiece,

means thereafter successively measuring the time for removal of an equivalent amount of the workpiece on each successive cycle,

and means for producing a signal when said any of said successive times exceeds the first-mentioned time by a predetermined percentage.

70. In a grinding machine, the combination comprising

a first support for a grinding wheel,

a second support for a workpiece,

means for moving said supports relative to one another to bring the workpiece and tool into contact,

means for measuring and storing the time grinding a first workpiece,

means for thereafter measuring the time for grinding a predetermined equivalent portion of subsequent workpieces,

and means for producing a dressing signal when the time for said subsequent grinding exceeds the first mentioned stored time by a predetermined precentage.

71. In a machine tool wherein a tool and a workpiece are moved relatively toward and away from each other to perform a work operation on the workpiece, the combination comprising

a first support for the tool,

a second support for the workpiece,

a rotatable feed device,

one of said supports being connected with said rotatable feed device so that upon rotation of said feed device said support is moved relative to the other support,

and an electric motor connected to the feed device,

means for applying a predetermined voltage to the motor just prior to contact with the workpiece so that the motor operates at constant current,

means for monitoring said current,

and means for producing a work contact signal when the increase in current due to contact between the workpiece and tool increases by a predetermined amount.

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